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Variation of Sabkha Soil Permeability Associated with Ions' Dissolution during Distilled Water Leaching

Fahad Abead Al-Otaibi [1)*]

[1)] Associate Professor, Civil Engineering Department, College of Technological Studies (CTS), Public Authority for Applied Education and Training (PAAET); P.O. Box 92420, Shuwaikh Area, State of Kuwait. * Corresponding Author. E-Mail: fo.alotaibi@paaet.edu.kw

ABSTRACT

Continuous flow of water passing through sabkha soil may increase the salt dissolution rate and is expected to lead to variation in soil permeability due to enlarging cavities between soil particles and consequently progressive collapse of the soil structure. Understanding the relationship between the dissolution of salts in sabkha soil and the variation of soil permeability is essential, especially in relation to type, rate and quantity, in order to ensure construction safety in these environments.

This study contributes toward shedding light on the relationship between soil permeability variation and the rate of salt dissolution from a sabkha soil sample under long-term distilled water leaching. Therefore, the permeability (K) and the concentrations of calcium (Ca^{+2}), sulphate (SO_4^{-2}), chloride (Cl^{-1}), magnesium (Mg^{+2}), sodium (Na^{+1}) and potassium (K^{+1}) ions were measured under conditions of protracted leaching at five pore volume intervals.

Results demonstrate a direct relation between sabkha soil permeability and the rate of ion dissolution. Cl^{-1}, SO_4^{-2} and Na^{+1} ions were expected to be the main ions whose dissolution led to an increase in soil permeability. This enabled us to take into consideration the reduction of these ions as one of the criteria to be addressed when investigating soil stabilization technique in addition to the geotechnical properties.

KEYWORDS: Sabkha soil, Dissolution, Sulfate, Calcium, Chloride, Sodium, Potassium, Leaching.

INTRODUCTION

The south coast of Kuwait consists primarily of sabkha deposits characterized by broad distribution, inhomogeneity and variability in particle size and degree of consolidation (Al-Hurban and Gharib, 2004). Derived from Arabic, the term "sabkha" refers to extensive and flat soil with salt encrustations found in environments with little or no precipitation and having a composition of clays, silts, sands and salty mixtures (Al-Alawi et al., 2019; Abu-Taleb and Egeli, 1981). A high level of moisture and a high groundwater table are additional defining features of sabkha deposits (Al-Amoudi et al., 1992; Al-Shamrani and Dhowian, 1997; Dhowian, 1991).

As explained by Ismael et al. (1986), there are high levels of salts in sabkha soils, serving as cementing agents, like gypsum, carbonates and chlorides. This is a serious issue for these types of soil, because salts significantly affect soil hydraulic conductivity and can therefore interfere with the geotechnical soil attributes if they are dissolved (Wei et al., 2020; Singh et al., 2011).

Al-Amoudi and Abduljauwad (1995a) reported a close relationship between the flow rate and implicitly sabkha permeability and the levels of sodium and chloride ions, with a marked decrease in flow rate being observed following minimization of ion levels after the first two days. In a different study, Ismael (1993a) conducted leaching tests on comparable Kuwaiti soils with salt content to analyze chloride dissolution, revealing that a correlation existed between the leaching effect and the degree of leaching-induced elimination of soluble salts.

The direct relationship between the leaching effect and the degree of leaching-caused elimination of soluble salts was confirmed by Al-Otaibi (2006) by conducting

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long-term leaching tests on soil samples with contamination and natural salt content from the south of Kuwait in order to examine the dissolution of salts. In a later study, the decrease in ion dissolution in sabkha soil with bitumen treatment was explored by Al-Otaibi and Wegian (2012), while the permeability behavior of sabkha soil with bitumen treatment in response to various added amounts of bitumen was investigated by Al-Otaibi et al. (2012).

Gypsum and anhydrite materials may dissolve quicker when exposed to rapid ongoing water flow and in turn, may cause the formation of fractures that can make the bedrock more permeable, thus diminishing the effectiveness of the grout curtain of the dam. Structure embedment occurs irregularly due to the formation of pores induced by rock dissolution (Memarian, 1992; 1995). Ahmad et al. (2012) observed that empty space expansion intensified the water flow through the soil at first, but subsequently the flow declined because of soil structural breakdown until an equilibrium was reached. Asghari et al. (2014) noted a comparable phenomenon when analyzing leaching soils with gypsum content, finding that during the initial testing phases, the permeability coefficient and levels of soil minerals varied significantly, before declining progressively and finally reaching stable levels. Meanwhile, Al-Amoudi and Abduljauwad (1995b) sought to determine how salt dissolution and soil permeability were correlated, discovering that there was a good correlation between the flow rate and implicitly sabkha permeability and the levels of sodium and chloride ions; furthermore, the flow rate dropped markedly with minimization of the ion levels following the first two days. Nashat (1990) focused on how samples of gypsum soil reacted to leaching at various hydraulic gradients and levels of stress, observing a varying reduction trend in hydraulic conductivity over time. The consequences of such variability included empty space expansion, gypsum elimination and obstruction of certain flow channels because of collapses caused by leaching, which can lead to problems in dewatering in fine soils (Vandanapu and Omer, 2020). Internal chemical processes between gypsum and water inside the gypsum deposits may affect the chemical composition of the released water (Al-Faragat, 2009). Thus, it can be concluded that unlike clay or silty clay soils, leaching effects have a more significant impact on coarse soils with gypsum content, like sands (Tatlari, 1996). An investigation carried out by Al-Otaibi (2020) revealed that corrosive anion dissolution was over 50% in some stages of leaching.

As discussed above, a serious issue associated with sabkha soils is their high salt content. The geotechnical attributes of soils can be severely impacted when the salts are dissolved and eliminated, causing gradual breakdown not only of the soil structure, but also of the structures underpinned by sabkha flats. When assessing soils intended to be employed as liners, hydraulic conductivity must be considered, as the surrounding medium may be contaminated with waste liquids because of fluctuating soil permeability. However, fluctuations in soil permeability caused by leaching of various ion types have not been researched as extensively as the characteristics of sabkha soils in Kuwait. Investigations have been conducted on stabilizing sabkha soil by using different additives or mechanical methods for altering the geotechnical properties of sabkha soils (e.g. Al-Alawi et al., 2020; Jung et al., 2020; Abbas, 2020; Wei et al., 2020), but these investigations have failed to consider problematic behavior, with the mechanisms of salt dissolution in relation to soil permeability requiring in-depth comprehension. Understanding this relation could then enable integration of the correlation between salt dissolution and sabkha soil permeability in mathematical models characterizing the response of soils to salts.

The following empirical work is meant to augment knowledge about the way sabkha soil permeability is affected by the salt dissolution rate under conditions of protracted leaching of distilled water.

MATERIALS AND METHODS

Soil Sampling

The southern sabkha flats situated 75 km south of Kuwait city were the area of sample collection (Figure 1). To acquire the samples, the researcher relied on personal experience as well as on the recommendations provided by other researchers (e.g. Al-Otaibi, 2006; Al-Otaibi et al., 2012; Al-Otaibi and Wegian, 2012; Al-Otaibi and Aldaihani, 2018).

Figure (1): Sampling location south Kuwait (Aldaihani et al., 2020)

September 2018 was chosen as the period for sampling for several reasons. First, dry conditions give rise to a cementation effect of various salt layers and crystals, so it was anticipated that the ground would be suitable for sampling. Secondly, the soils had maximum salt content following evaporation in the summer season. The adopted sampling strategy involved arbitrary extraction of 10-kg soil samples at a depth of 10-50 cm from 20 pits within a perimeter of (100×100) m in the chosen area. As illustrated in Figure (2), the sampling pits revealed that cemented soils of different thicknesses dominated the external surface of the sampling area.

Figure (2): Outer surface soil crust of the sampling pit

Figure 3 shows that the surface area displayed crystals of gypsum ($CaSO_4{\bullet}2H_2O$) as well as aggregations of loose crystals of sodium chloride (NaCl) formed when tidal water evaporated. Silty sands with poor cementation were observed beneath the cemented soils noted at various levels and differing in thickness. As indicated by several researchers, the recurrent evaporation of flood waters with high content of dissolved salts is the cause of such variability (Livneh et al., 1998; Yechieli and Wood, 2002).

Figure (3): Soil aggregation

Sample Preparation

A homogeneous composite was obtained by rigorous mixing of every extracted soil sample in a container. The composite was then divided into four parts to attain a representative sample. The samples were dried *via* exposure to air. The necessary amount of soil was dried in an oven at a temperature of around 60°C prior to every test, due to evidence that soil properties are substantially altered by high temperatures (Ismael, 1993b). Rubber hammers were employed to delicately divide the soils before sieving them with a 4.75-mm mesh. Sieving was followed by rigorous soil mixing, homogenization and introduction in a sizable container.

Index Properties

The physical characterization of the soil samples was evaluated through several tests, including particle size distribution, consistency limits, specific gravity and compaction tests. Furthermore, due to having a substantial content of fines, the soil samples were mechanically sieved and subjected to hydrometer analyses. These tests were performed according to the ASTM D422 (ASTM D422 1998). Particle size distribution D10, D30, D60, the uniformity coefficient (Cu) and the coefficient of curvature (Cc) were determined.

The ASTM D4318 was followed when assessing the plasticity features of the samples of natural sabkha soils and the two values served as the basis for determining the plasticity index (PI). Furthermore, the unified soil classification was applied to categorize the samples (ASTM D4318 1995). The ASTM D854 was followed to calculate the specific gravity (Gs) or particle density of various samples with the use of a pycnometer. The two tests were averaged to obtain the values (ASTM D854 2014). Maximum dry density (MDD) and optimum moisture content (OMC) were determined by performing the compaction test *via* the modified Proctor technique in accordance with the ASTM D1557 (ASTM D1557 2012).

A sample of sabkha soil minerals was tested using XRD in accordance with the protocol of the Kuwait Institute for Scientific Research (KISR).

Leaching Test

As explained by Al-Zgry (1993), the process of leaching involves dissolution and removal of the soluble components of a material through percolation of distilled water under artificial pressure through that material. The present study was primarily concerned with determining the level of leaching of chloride (Cl^{-1}) and sulphate (SO_4^{-2}) anions and of calcium (Ca^{+2}), magnesium (Mg^{+2}), sodium (Na^{+1}) and potassium (K^{+1}) cations.

Leaching Process

This study followed the leaching procedure proposed in previous studies (Al-Otaibi, 2006; Al-Otaibi et al., 2012; Al-Otaibi and Wegian, 2012) to carry out the leaching process. The compaction parameters of the representative sample derived from the modified compaction test were used to compact the sample in the leaching cell on five layers. To maintain the temperature and pressure at fixed levels, the temperature and pressure conditions associated with the complex subsurface were not simulated. A space with temperature regulation (± 0.5°C variation) was the setting for the procedure.

The sample was at first saturated through percolation of the distilled water from the bottom at a reduced pressure of 7.0 kPa. On the following day, sample percolation was conducted from top to bottom at 35.0-kPa pressure. As suggested by previous studies (e.g. Al-Otaibi, 2006; Al-Otaibi et al., 2012; Al-Otaibi and Wegian, 2012), the chosen pressure was equivalent to 3.5-m water head to expand the leached pore volumes within an acceptable amount of time. For every pore volume, the leachate was kept in a plastic bottle and refrigerated until needed.

Leachate Type

Since the rate of salt dissolution was anticipated to be higher, distilled water was employed to account for the worst possible situation (Al-Amoudi and Abduljauwad, 1994; Al-Sanad and Al-Bader, 1990; Ismael 1993a; Al-Otaibi, 2006; Al-Otaibi et al., 2012; Al-Otaibi and Wegian, 2012). Furthermore, to attenuate the impact on chemical analysis, distilled water was employed for leaching purposes as well, because its ion concentration is minimal.

Pore Volume Determination

Weighing of the cell was conducted when the latter was void, while weighing of the soil was conducted when the latter was dry, prior to packing. The packing of the cell was subsequently conducted when the latter was wet, followed by weighing. The discrepancy among the dry cell coupled with the dry soil and the packed, saturated column was the same as the water pore volume.

Leachate Chemical Analysis

The dissolution features of the sabkha soil samples were distinguished by conducting chemical analyses for the chosen leached pore volume at various points during the period of leaching. These analyses were based on the ions that the XRD analysis identified as occurring in sabkha soil; namely, the Cl^{-1} and SO_4^{-2} anions and the Ca^{+2}, Mg^{+2}, Na^{+1} and K^{+1} cations. More specifically, Inductive Coupled Plasma Optical Emission Spectroscopy (ICP-OES) was conducted to analyze the soil cations, while Ion Chromatography (IC) was conducted to analyze the soil anions (HMSO, 1980). Total dissolved salts (TDSs) for pore volume samples were dried in the oven to constant weight at a temperature of 105 ± 2°C for the purpose of gravimetric determination (U.S. EPA, 1998). Analysis of additional ions was conducted in the laboratory of the Ministry of Electricity and Water.

Coefficient of Permeability Measurement

In keeping with Mohammed (1995) and Al-Otaibi (2006), the permeability coefficient of sabkha soils (k) was determined *via* the leaching cell test, which enabled examination of the permeability of the sabkha soil sample over the long term. After measurement of the water volume (Q ml) flowing through the sample over a particular time interval (t seconds) whilst subjected to the hydraulic gradient effect, k was determined by using Darcy's Law.

RESULTS AND DISCUSSION

Soil Characterization

Soil Mineralogy

To determine the minerals present in the sabkha soil sample and finish the assessment of the dissolution process, X-ray diffractometry was undertaken and the outcomes obtained were informed by an approximation of the peak high intensities on the diffractometer trace for every mineral. As can be observed in Figure (4), sabkha soil was primarily composed of silicon dioxide (SiO_2) in a proportion of around 35%, gypsum ($CaSO_4{\cdot}2H_2O$) in a proportion of 25%, halite (NaCl) in a proportion of 20% and calcite ($CaCO_3$) in a proportion of 15%. Sabkha soil also contained lower levels of aragonite, which is an unstable form of calcium carbonate with the same chemical formula ($CaCO_3$), but with a differently shaped crystal. These figures are consistent with those obtained from the analysis of sabkha soils in other areas of Kuwait (Ismael, 1993b; Al-Otaibi, 2006).

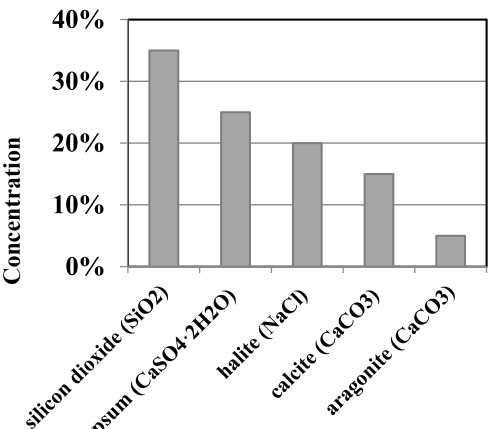

Figure (4): The X-ray diffraction test results

Soil Physical Properties

Figure 5 illustrates the representative grain size distribution with superior and inferior grading curve limit for the 20 samples of sabkha soils extracted arbitrarily from the chosen area.

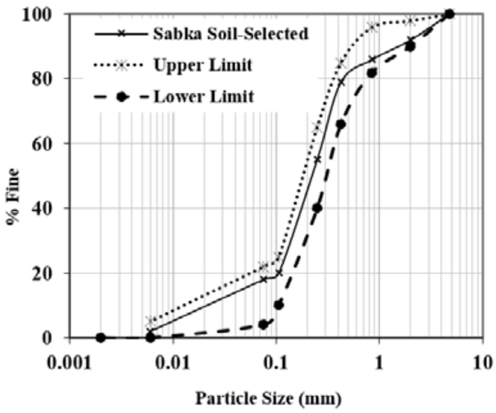

Figure (5): Limits of the grain size distribution curves for the tested south sabkha soil samples and the selected sample

It can be seen clearly from the figure that the limits of the grain-size distribution curves obtained from sieve and hydrometer tests for sabkha soil samples were not widely varying within the tested location. Soil gradation analysis results for some of the randomly collected soil samples and from the location are summarized in Table 1.

Table 1. Physical characteristics of some south sabkha soil samples

MDD (kN/m³)	19.02	18.89	18.82	18.65
OMC%	9.30	9.55	10.30	10.98
GS	-	-	2.79	-
USC	SP-SM	SP-SM	SP-SM	SP-SM
PI%	4.5	2.0	4.0	2.5
LL%	21.5	19.5	22.5	16.5
PL%	17.0	17.5	18.5	14.0
Fine%	11.0	17.0	18.0	16.0
Cc	0.7	3.8	3.6	4.2
C_u	3.6	17.5	12.3	13.5
D_{60}	0.28	0.28	0.26	0.27
D_{30}	0.125	0.13	0.14	0.15
D_{10}	0.077	0.016	0.021	0.02
Samples Locations	***Sbk-1**	***Sbk-8**	***Sbk-13**	**South *Sbk Selected**

Sbk means Sabkha Soil.

From the data shown in Table 1, it is clear that the sabkha soil samples had low plasticity, which could be due to low fine contents and reduced amount of clay particles (Elsawy and Lakhoit, 2020; Arora, 1997). On the other hand, it should be considered that the high concentrations of soluble salts can affect the consistency limits of a soil (Mahasneh, 2004). Sabkha soil samples were classified as poorly graded silty sand (SP-SM) according to the Unified Soil Classification System (USCS).

In general, physical characteristics are in good agreement with the findings reported by other studies (e.g. Al-Sanad, 1986; Ismael, 1993-b; Al-Hurban and Al-Gharib, 2004; Al-Otaibi, 2006; Al-Otaibi et al., 2012; Al-Otaibi and Aldaihani, 2018) that investigated sabkha soils from southern Kuwait.

It was decided to conduct the leaching test on the soil sample depicted in the figure, as it was representative of the samples collected from the location. The specific gravity value of the chosen sample was 2.8. In general, the specific gravity value of sabkha soils is lower than that of typical sands or silty sands, which has been attributed to the combined impact of the low oven temperature (60°C) of specific gravity and the high salt content of sabkha soils (Al-Amoudi et al., 1992) and may require corrections due to the dissolution of the salts (Nusier et al., 2008).

Compaction Characteristics

Figure 6 illustrates the modified Proctor compaction test results for the tested soil samples. It can be seen in this figure that the compaction test parameters are in a close range. The MDD values ranged from 18.38 kN/m^3 to 19.23 kN/m^3 at OMC ranging from 9.48% to 10.92%.

Table 2 summarizes the OMC and MDD values obtained from the modified Proctor compaction test results for some soil samples.

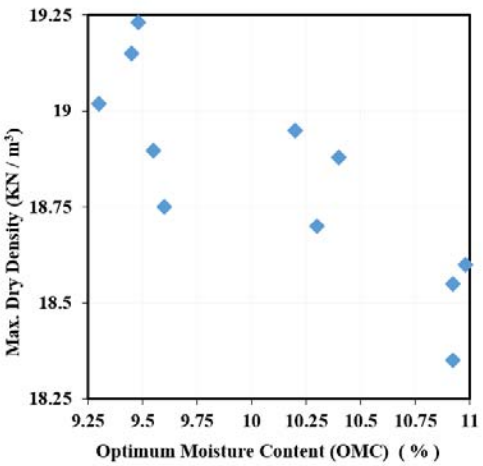

Figure (6): Maximum dry density values *versus* optimum moisture content for randomly collected sabkha soil samples

The MDD and OMC values observed in this study are consistent with the findings of other studies concerning sabkha soils in Kuwait and the Gulf region (e.g. Al-Sanad, 1986; Ismael, 1993-b; Al-Otaibi, 2006; Al-Otaibi et al., 2012).

Dissolution Characteristics

The leached pore volumes were chemically analyzed and the concentrations of leached Cl^{-1} and SO_4^{-2} anions and Na^{+}, Ca^{+2}, Mg^{+2} and K^{+1} cations from the tested sabkha are depicted in Figure 7 and numerically summarized in Table 2. Results reveal a high concentration of SO_4^{-2}, Na^{+1} and Cl^{-1} among the tested ions across the first ten leached pore volumes, where the SO_4^{-2} ion was the highest till the twentieth pore volume. When analyzing the leached fluids for the total dissolved salts, it was found that the SO_4^{-2}, Na^{+1} and Cl^{-1} contents were generally more than half the quantity of the total dissolved salts determined through the ion chromatography technique (Table 2).

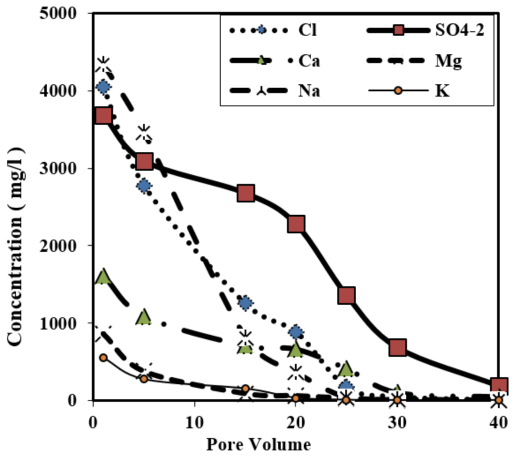

Figure (7): Changes in ions' concentrations in effluents in tested sabkha soil sample

Table 2. Chemical analysis of leached pore volumes

PV	Cl^{-1} mg/L	SO_4^{-2} mg/L	Ca^{+2} mg/L	Mg^{+2} mg/L	Na^{+1} mg/L	K^{+1} mg/L
1	4100	3725	1650	880	4650	553
5	2830	3129	1120	431	3270	277
15	1295	2730	731	93	860	155
20	920	2300	677	65	420	35
25	195	1380	433	33	45	10
30	53	720	117	12	23	5
40	10	215	53	10	8	5

Figure 7 clearly shows a trend of reduction in the concentrations of Cl^{-1}, SO_4^{-2}, Na^{+1}, Ca^{+2}, Mg^{+2} and K^{+1} at different rates with pore volumes. The variation in concentrations shown in the figure and summarized in the table can be attributed to the degree of solubility of the salts and their confirmed presence in the tested sabkha soil sample. The presence or predominance of gypsum ($CaSO_4{\cdot}2H_2O$) and halite (NaCl) minerals is expected to be the factor that strongly influences the high dissolution concentrations of their ions. The extent of gypsum dissolution in soil has been measured from increases in the concentrations of Ca^{+2} or SO_4^{-2} in the soil solution (Nanthi et al., 1991).

The concentrations of Na^{+1}, Mg^{+2} and K^{+1} anions diminished sharply after 20 pore volumes. The continuous and almost constant dissolution of Ca^{+2} ions across the tested pore volumes may be attributed to the high content of calcium-based soluble compounds in the parent sabkha soil; i.e., gypsum and calcium carbonate (calcite and aragonite), which was shown in the mineralogical analysis. Gypsum is classified as a moderate soluble salt, with solubility of the hydrated type in pure water of 2 g/l (Hesse, 1971).

A similar finding was reported by Al-Amoudi and Abduljauwad (1995a) during their investigations on sabkha soils and was attributed to the calcareous nature of the leached soil samples.

Soil Permeability Measurements

Permeability values for the sabkha soil sample were measured at different pore volumes and the leaching test results are presented in Table 3 and displayed in terms of permeability *versus* pore volumes in Figure 8. The variation percentages in the table were calculated with respect to the initial permeability value as follows:

$$\text{Variation (\%)} = ((K_i - K_0)/ K_0) *100$$

where:

K_0: initial permeability.

K_i: permeability at any interval.

The rate of increase in the coefficient of permeability values varied along the leached pore volumes. The initial coefficient of permeability for the compacted sabkha soil samples was $5.535\text{x}10^{-06}$ cm/s, which was in the range of permeability values for tested sabkha soil in the area (Al-Otaibi, 2006; Al-Otaibi et al., 2012). The infiltration increased rapidly with continuous leaching and reached almost 155% in the first thirteen pore volumes, with the measured permeability at that stage being $14.148\text{x}10^{-06}$ cm/s. With continuous leaching, the soil permeability for the tested sabkha soil sample remained approximately constant with time, as shown in Figure 7. Soil permeability at that stage of leaching varied from 14.148^{-06} cm/s to 15.418^{-06} cm/s at 13 and 23 pore volumes, respectively.

A higher rate of increase in the infiltration was observed in the sabkha soil sample at the stages from 23 to 30 leached pore volumes, where the permeability increased from $15.418\text{x}10^{-6}$ cm/s to $21.418\text{x}10^{-6}$ cm/s, representing an increase of 287%. After that stage, the permeability values became almost constant, with an average value of $21.422\text{x}10^{-6}$ cm/s until leaching stopped.

Table 3. Permeability values for the sabkha soil sample and the variation percentages at different pore volumes

PV	K(cm/sec.) x 10^{-6}	Variation (%)
1	5.535	0.0
2	5.710	3.2
3	5.954	7.6
4	6.563	18.6
5	6.869	24.1
6	7.175	29.6
13	14.148	155.6
17	14.806	167.5
23	15.418	178.5
30	21.424	287.1
34	21.222	283.4
37	21.422	287.0

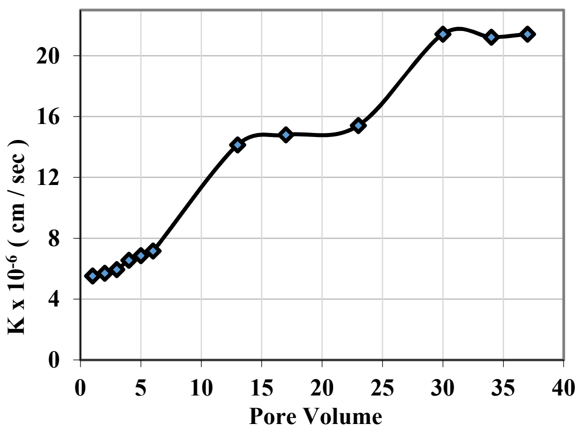

Figure (8): Permeability values *versus* leached pore volumes for the sabkha soil sample

Correlation between Permeability and Salts' Dissolution

To evaluate the salt dissolution effect on the sabkha soil permeability, the variation in the sabkha soil permeability and the leached ion concentrations at different measured pore volumes are presented in Figures 9 and 10.

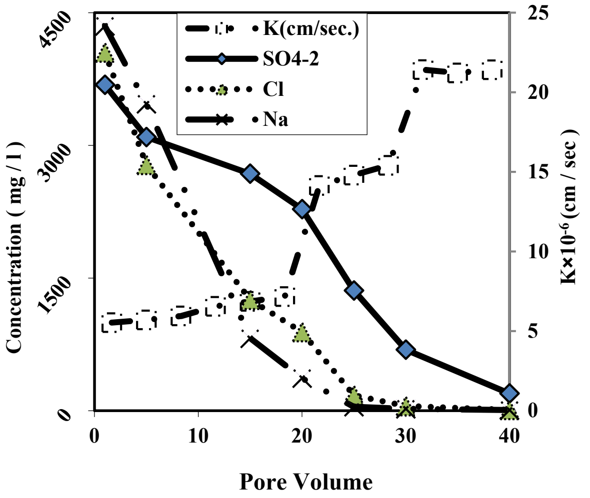

Figure (9): Variation of sabkha soil permeability with Cl^{-1}, SO_4^{-2} and Na^{+1} dissolution

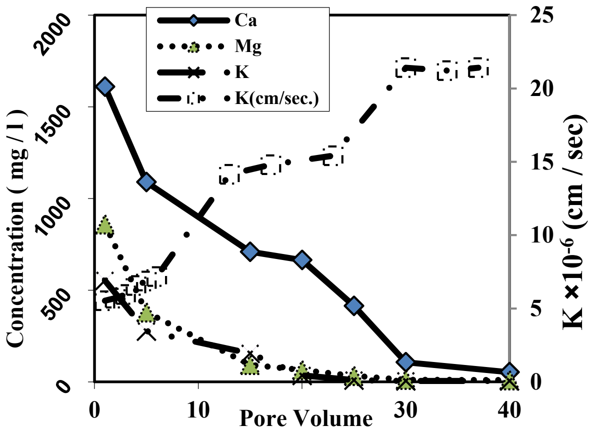

Figure (10): Variation of sabkha soil permeability with Ca^{+1}, Mg^{+2} and K^{+1} dissolution

Figure 9 shows clearly that the higher permeability rate increase was almost in the range of increase of dissolution of SO_4^{-2}, Na^{+} and Cl^{-1}. Similarly, Figure 10 shows that the high dissolution rate of Na^{+1}, Mg^{+2} and K^{+1} cations was within the range of sabkha soil permeability increase, but with lower concentration rate.

The increase in permeability was more rapid and was almost 2.6-folds in the first 13 pore volumes, which correlated very well with the higher dissolution rate of Cl^{-1}, SO_4^{-2} and Na^{+1} ions, as shown clearly in Figure 9. This higher infiltration rate may be attributed to the wider opened channels between soil particles due to the dissolution of Cl^{-1}, SO_4^{-2} and Ca^{+2} ions (Al-Otaibi and Wegian, 2012). Similarly, Ahmad et al. (2012) concluded that the flow of water through gypseous soil increased initially with time due to the enlargement of voids.

To show clearly the amount of dissolute ions, their concentrations are calculated as a percentage of TDS as follows:

% Diss. of Ion = (Concentration at any PV / TDS at the same PV) ×100.

The calculated values are summarized in Table 3 and shown in Figure 11.

Table 4. Salt dissolution percentages with respect to TDS at different pore volumes

PV	% Diss. Cl^{-1}	% Diss. SO_4^{-2}	% Diss. Na^{+1}	% Diss. Ca^{+2}	% Diss. Mg^{+2}	% Diss. K^{+}
1	27	24	29	11	6	4
5	25	28	31	10	3	2
15	22	47	14	12	2	3
20	21	53	9	15	2	1
25	9	67	2	20	2	0
30	6	78	3	12	1	1
40	4	69	3	19	4	2

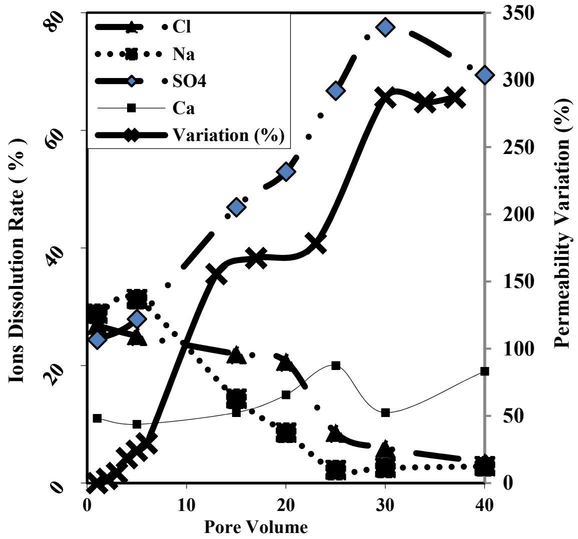

Figure (11): Variation of permeability with ions' dissolution rate

The results indicated an increase in the SO_4^{-2}, Na^{+1} and Cl^{-1} dissolution rate, which reflected the presence of those salts in the soil. In addition, the increase in water flow is expected to be a factor in the greater dissolution of some salts. For example, the dissolution rate constants for gypsum depend on many factors, which include the nature of the gypsum source, particle size, ionic strength of the medium, intensity of stirring, water flow velocity and temperature (Nanthi et al., 1991; Al-Rawi et al., 2011). The increase in the concentration of total dissolved solids was observed by Moqbel and Abu-El-Sha'r (2018) in their contaminant transport model and was expected to be due to the movement of high-salinity water toward the pumping wells used for domestic purposes.

The reduction in the dissolved solids and the increase in the permeability with continuous leaching were observed by Aiban (2007) during his investigation on fine-grained calcareous sediment. Similar behavior was reported by Asghari et al. (2014) during their investigations on leaching gypseous soils, where they reported high variability in permeability coefficient and concentration of minerals in the soil in the early stages of the tests. Subsequently, the changes gradually decreased and tended towards constant values.

The results of the current study indicated that Cl^{-1}, SO_4^{-2} and Na^{+1} were the main ions and their high dissolution rate was expected to be the main factor in increasing the sabkha soil permeability, as some salts present in the soil have a great effect on the hydraulic conductivity of the soil (Singh et al., 2011).

CONCLUSIONS

The purpose of this work was to investigate the correlation between ion dissolution and the permeability of sabkha soil. Soil samples from southern Kuwait were classified as poorly graded silty sand (SP-SM) according to the USCS, with a specific gravity of 2.8. Mineralogical soil characterization revealed that the components of the sabkha soil were silicon dioxide (SiO_2), gypsum ($CaSO_4 \cdot 2H_2O$), halite (NaCl) and calcite ($CaCO_3$).

Representative sabkha soil sample was leached with distilled water under 35 kPa air pressure. The results obtained in this study support several conclusions:

(1) The initial sabkha soil sample permeability was 5.535×10^{-6} cm/s and increased to 155% at thirteen pore volume stage.

(2) The rate of increase in the sabkha soil permeability values differed along the leached pore volumes.

(3) At the end stages of leaching, the sabkha soil coefficient of permeability reached 21.42×10^{-6} cm/s, representing 287% of the initial permeability value.

(4) There was a high concentration of SO_4^{-2}, Na^{+1} and Cl^{-1} among the tested ions across the first ten leached pore volumes, where the SO_4^{-2} ion concentration was the highest until the twentieth pore volume.

(5) Cl^{-1}, SO_4^{-2} and Na^{+1} are expected to be the main ions whose dissolution increases the soil permeability.

With regard to the stabilization technique, a stabilizer should be selected based on its ability to provide an impermeable layer to prevent direct contact between water and salt particles, which may reduce the salt leaching process.

FUTURE STUDIES

This and other following studies on different sabkha soil compositions will be used to develop a model that could predict hydraulic conductivity variation for sabkha of varying composition.

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